Wavelets at the Galactic Center

Sam McDermott

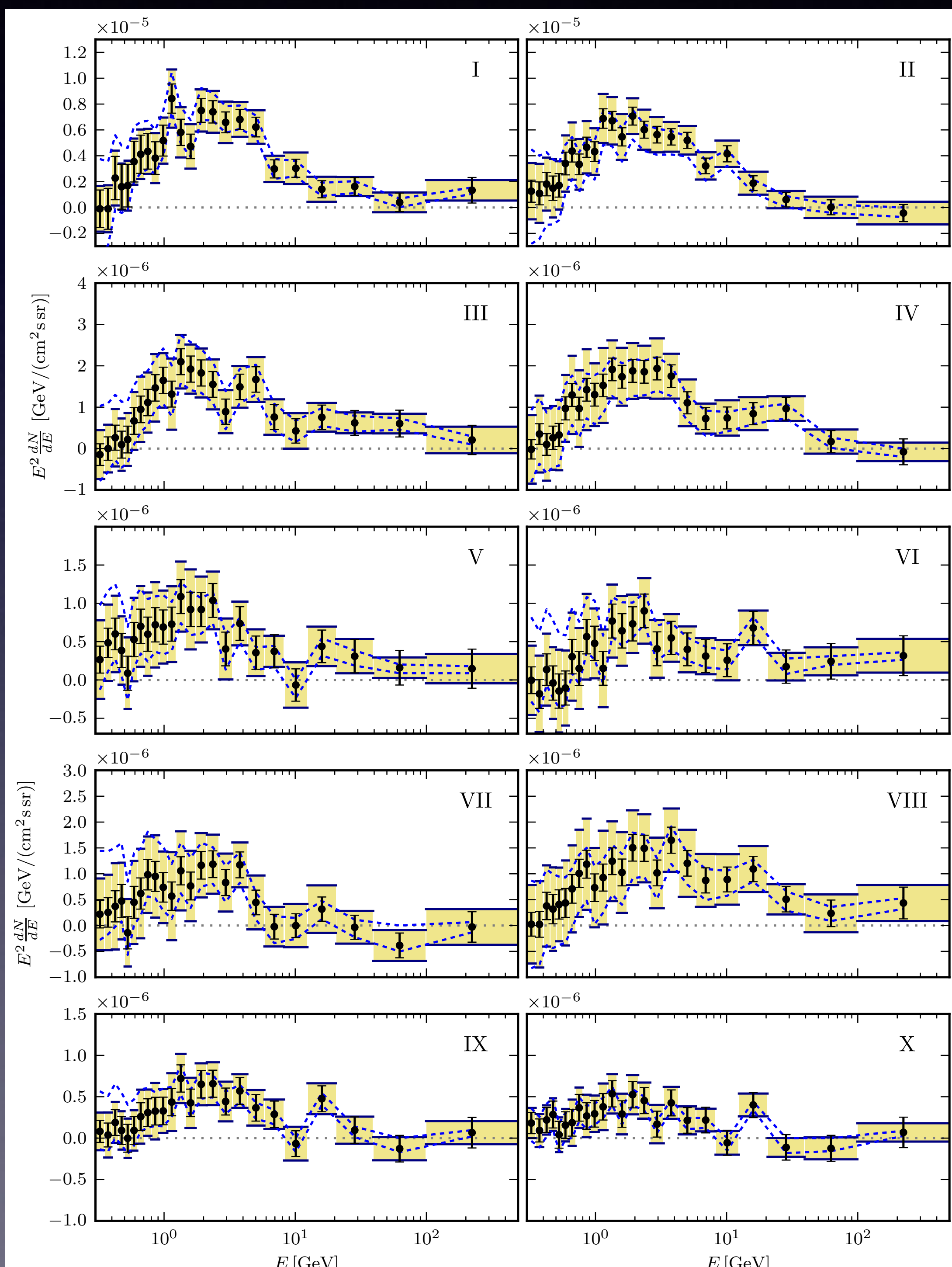
Based on:

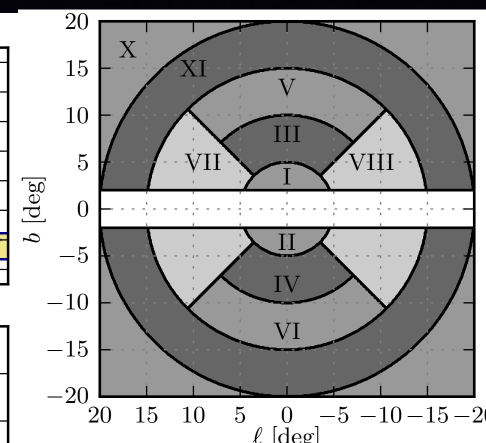
SDM, I. Cholis, P. Fox, S. K. Lee
(preliminary / in progress)

Brookhaven Forum, 10/08/15

Stony Brook University

Excess photons

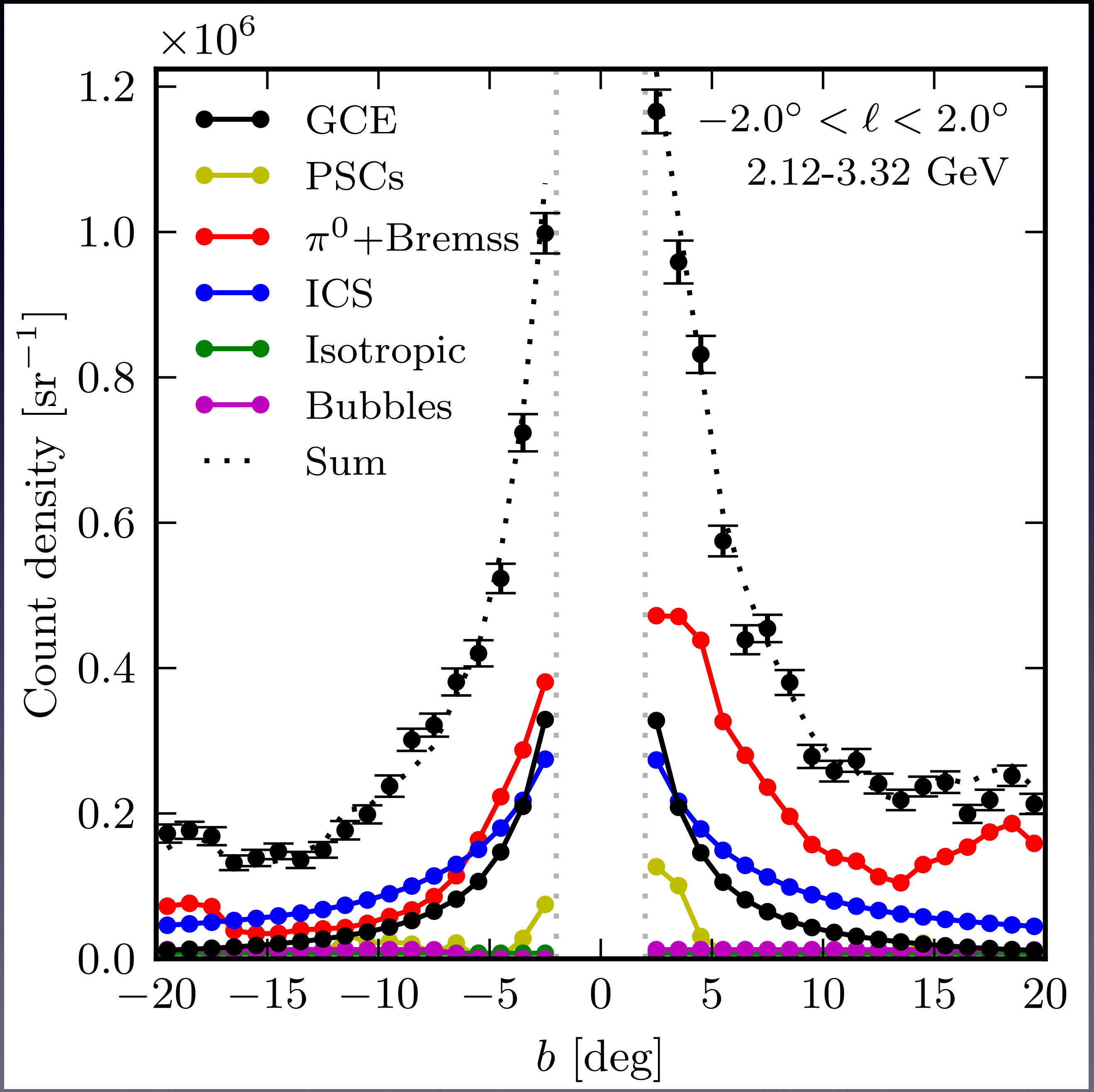




Calore, Cholis, Weniger
1409.0042

$E_{\gamma,max}$ ~ 2 GeV, robust to changes in diffuse template

Total Normalization



1409.0042

at energies of interest, ~ O(30%) of total flux

“Introduction”

existence of a significant new gamma-ray emission from Galactic Center is pretty robust, but…

- … diffuse templates house large, energy-dependent uncertainties
- … serious caution and healthy skepticism are required when interpreting as BSM physics
- … a few opportunities so far that “could have been convincing” (either way) have not panned out

How else can we convince ourselves this is or isn’t dark matter?

How else can we convince ourselves this is or isn't dark matter?

Particle physics ideas

How else can we convince ourselves this is or isn't dark matter?

Particle physics ideas

New observational ideas

Current Technique

Test *assumption of dark matter annihilation*:

- statistical discrimination (χ^2 test) between fits with and without signal template
- fits with template do better

Current Technique

Test *assumption of dark matter annihilation*:

- statistical discrimination (χ^2 test) between fits with and without signal template
- fits with template do better

…but what if there is a *totally different shape* on the sky that was not adequately tested?

Current Technique

Test *assumption of dark matter annihilation*:

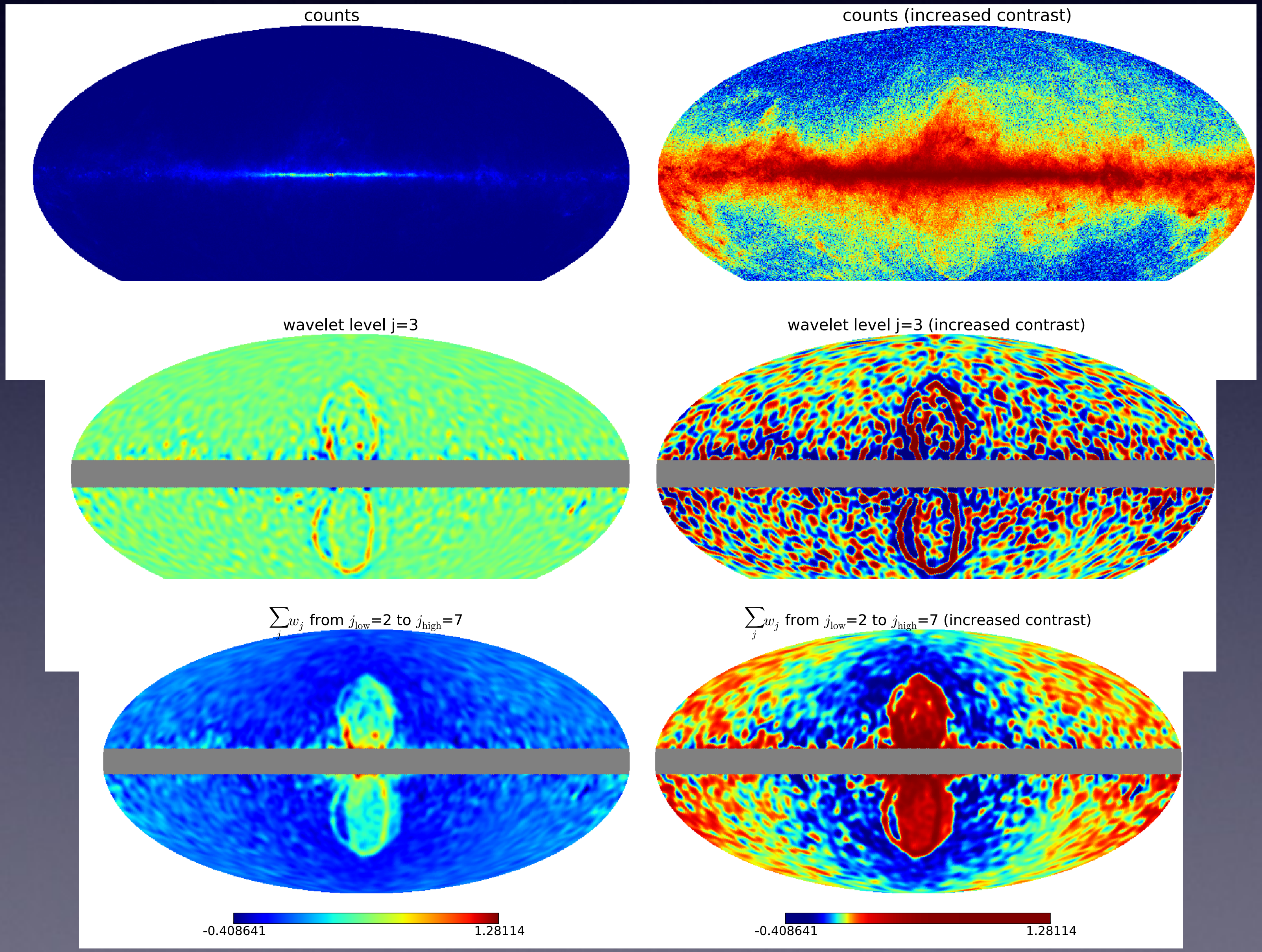
- … ween … late
- …

It would be nice to find evidence without making this assumption!

…but what if there is a *totally different shape* on the sky that was not adequately tested?

Rudimentary Image Processing, with Wavelets

in development with Paddy Fox,
Ilias Cholis, and Samuel K Lee



Wavelets

Allow analysis sensitive to both location and scale

Used for a wide variety of industrial and academic applications:

- image compression (JPEG-2000)
- fast astrophysical signal identification
- cochlear transforms (mimic hearing)
- image denoising
- jets (this is still in its infancy…)
- etc.**

What are wavelets?

wavelet coefficients

original signal

$$W(a,b) = \frac{1}{\sqrt{a}} \int f(x) \psi^* \left(\frac{x-b}{a} \right) dx$$

scale

position

mother wavelet
(different choices)

$$\int \psi(x) dx = 0$$

$$\int |\psi(x)|^2 dx = 1$$

$\psi(x) \in \mathbb{L}^2(\mathbb{R})$ and

$$\frac{1}{\sqrt{a}} \psi \left(\frac{x-b}{a} \right) \in \mathbb{L}^2(\mathbb{R})$$

for $a, b \in \mathbb{Z}$

What are wavelets?

wavelet coefficients

original signal

$$W(a,b) = \frac{1}{\sqrt{a}} \int f(x)\psi^* \left(\frac{x-b}{a}\right) dx$$

scale

How (and why) do they work?

ner wavelet

ent choices)

$$\int \psi(x)dx = 0$$

$$\int |\psi(x)|^2 dx = 1$$

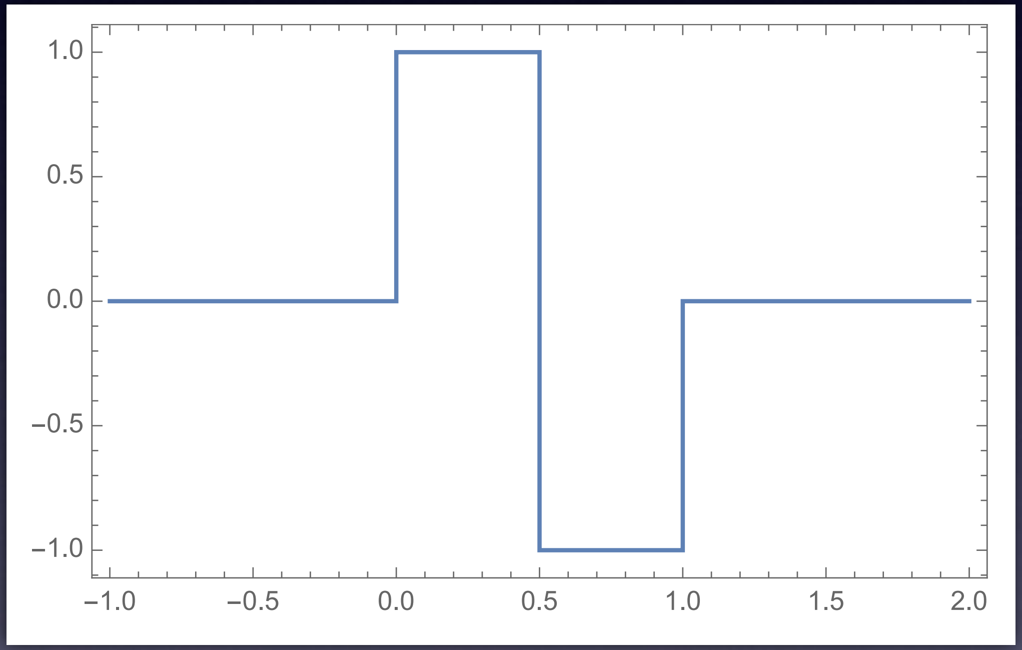
$\psi(x) \in \mathbb{L}^2(\mathbb{R})$ and

$$\frac{1}{\sqrt{a}}\psi\left(\frac{x-b}{a}\right) \in \mathbb{L}^2(\mathbb{R})$$

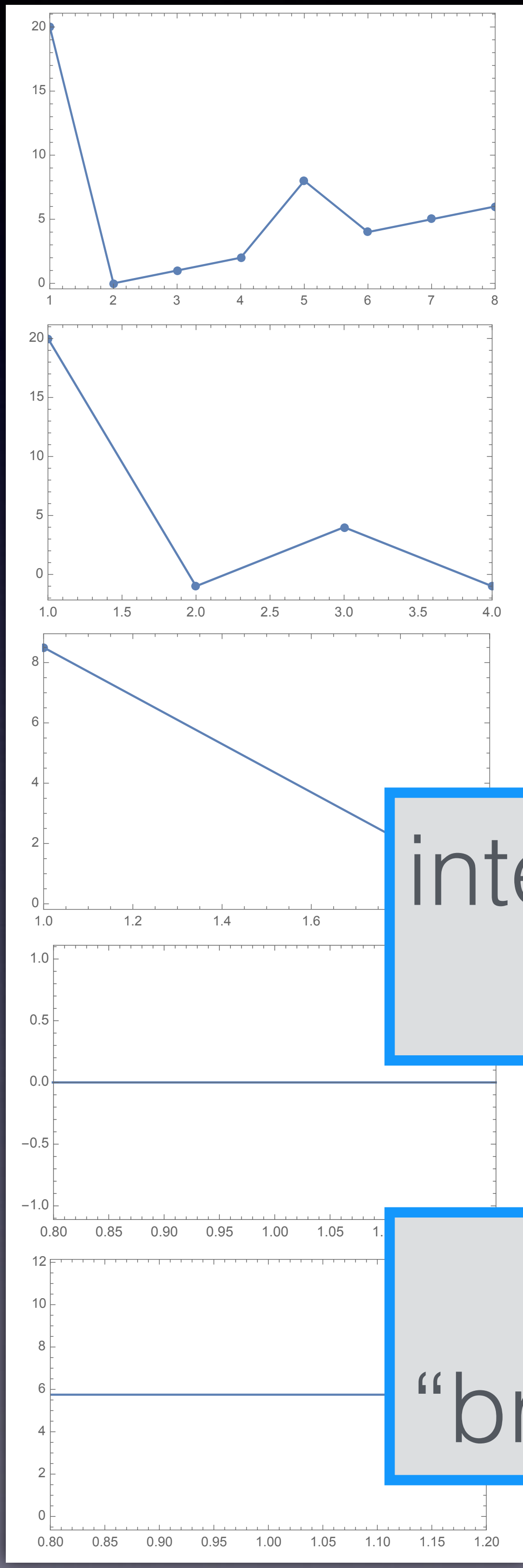
for $a, b \in \mathbb{Z}$

Haar

The Haar wavelet:



differences adjacent cells (or pixels, etc.)



signal

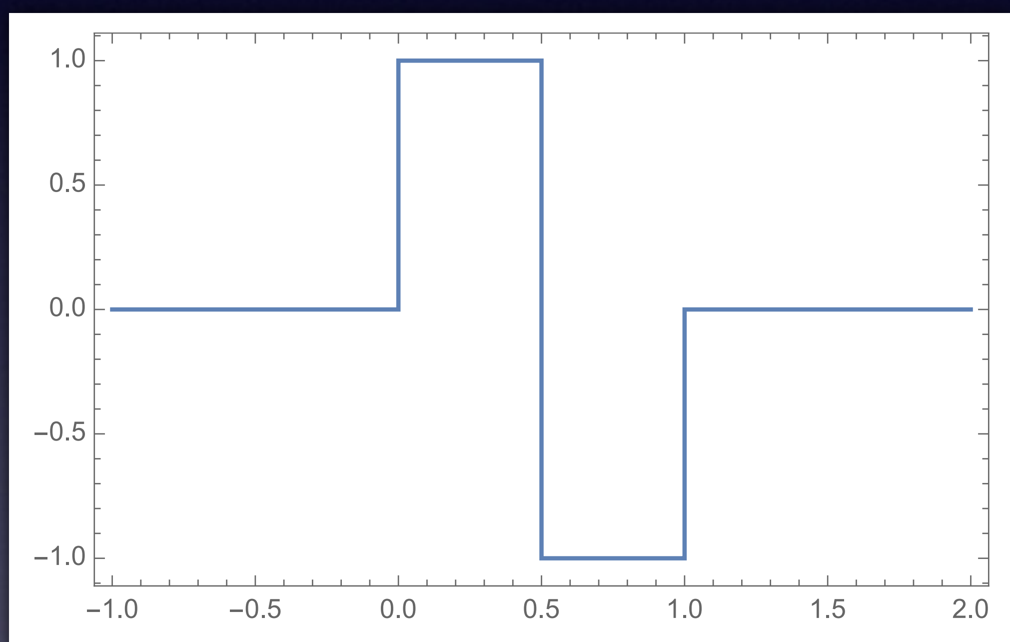
small scale

intermediate scales

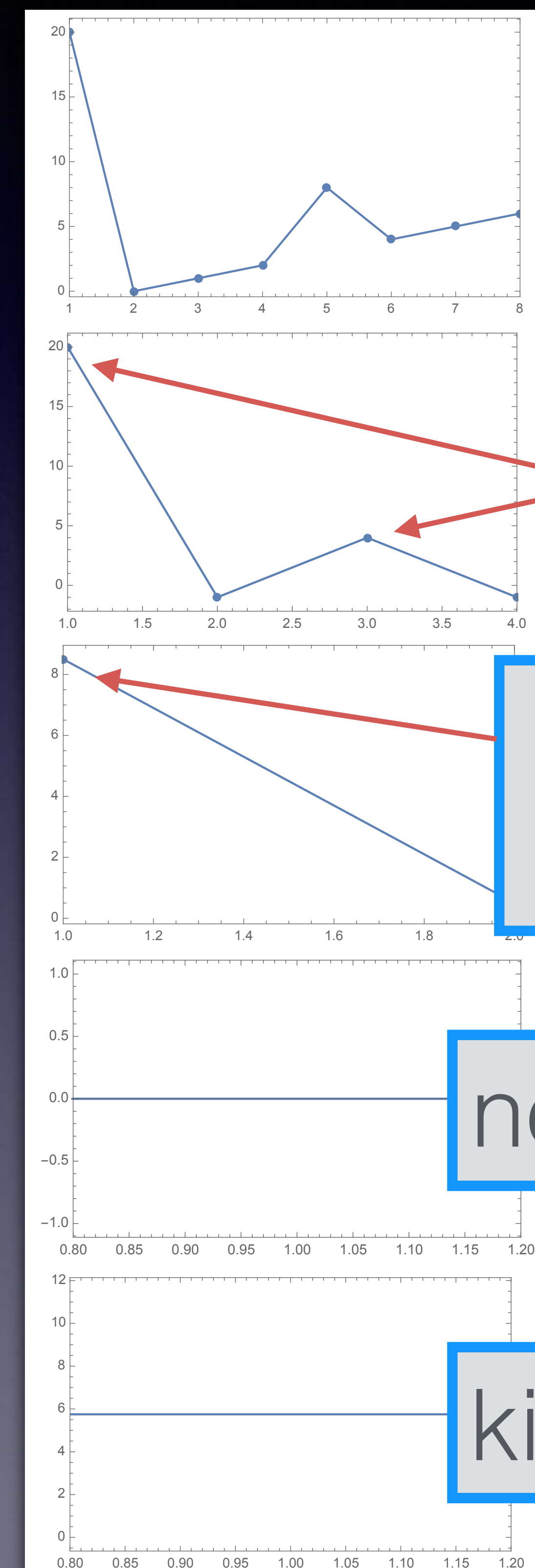
overall “brightness”

Haar

The Haar wavelet:



differences adjacent cells (or pixels, etc.)



signal

edges!

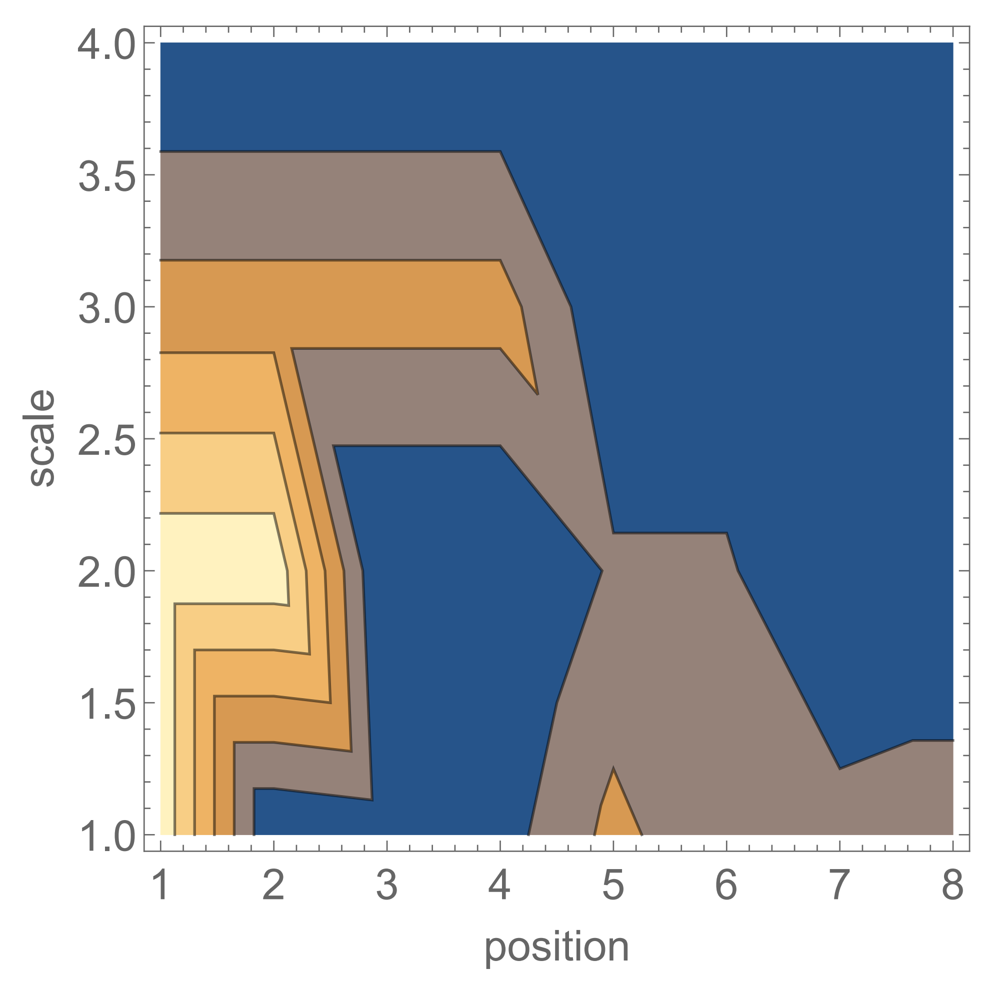
this edge is bigger!

no structure

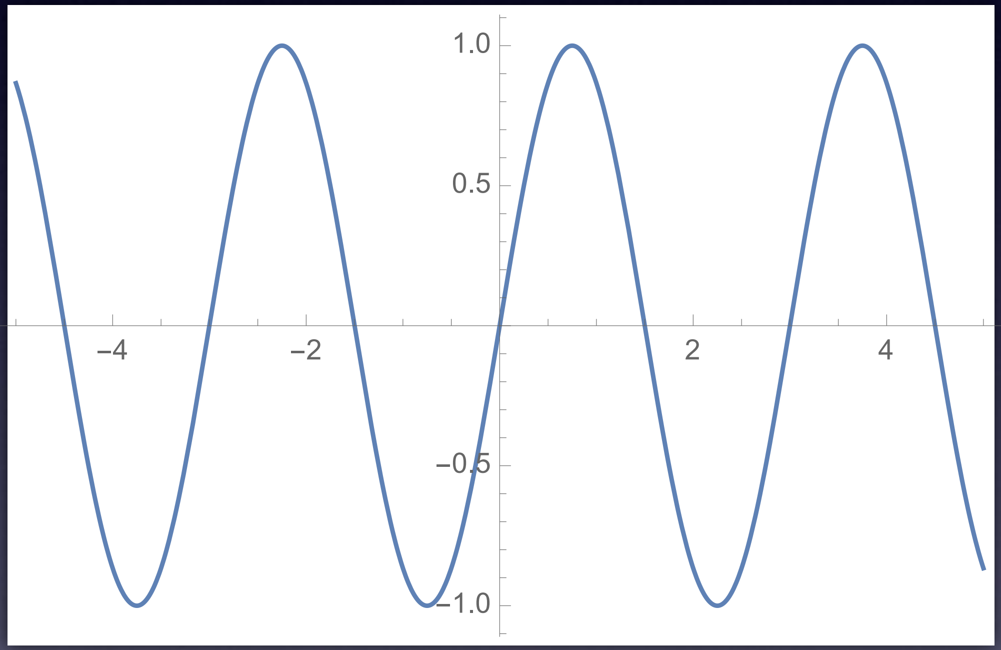
kinda bright

Alternate Form

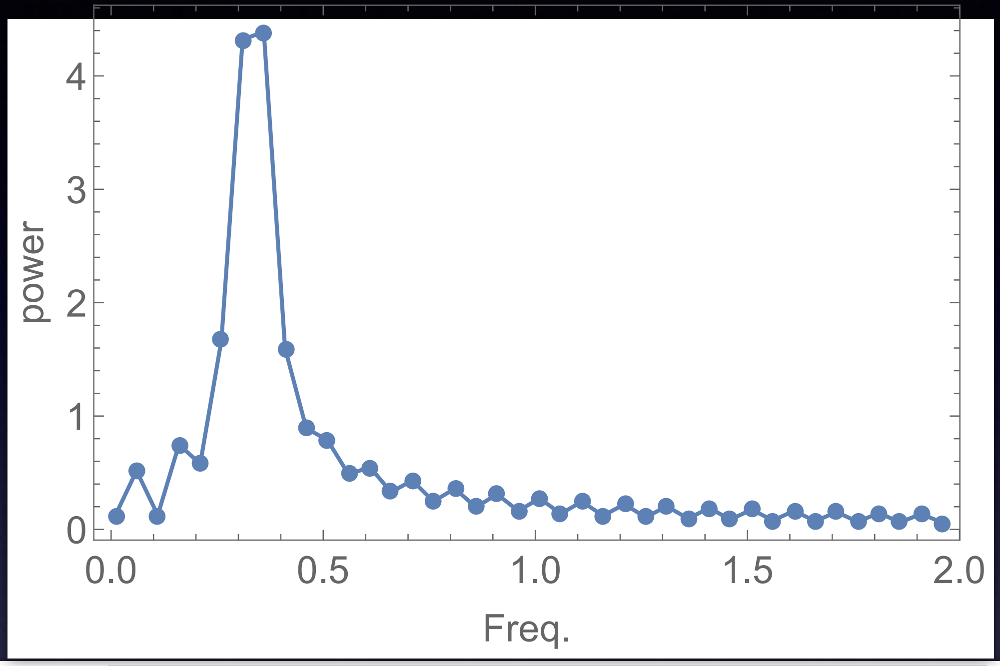
same information in 2d
(position-scale space)



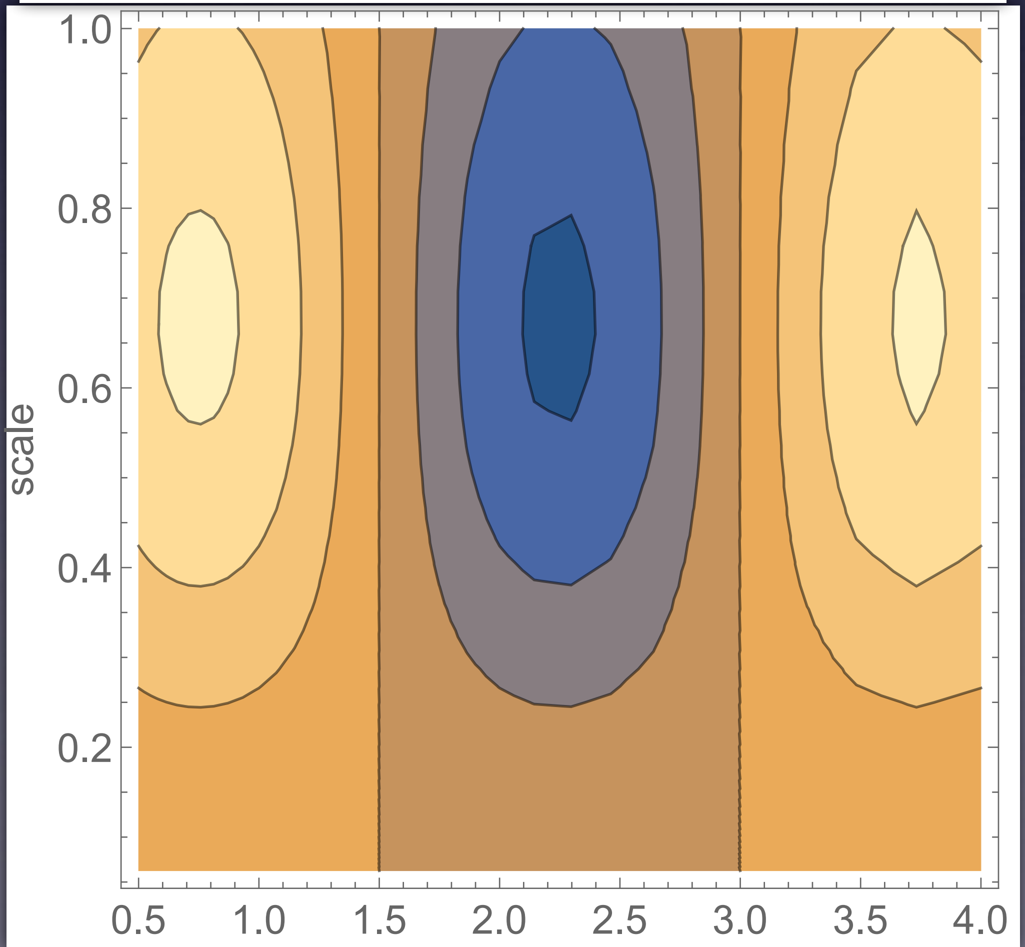
sine wave



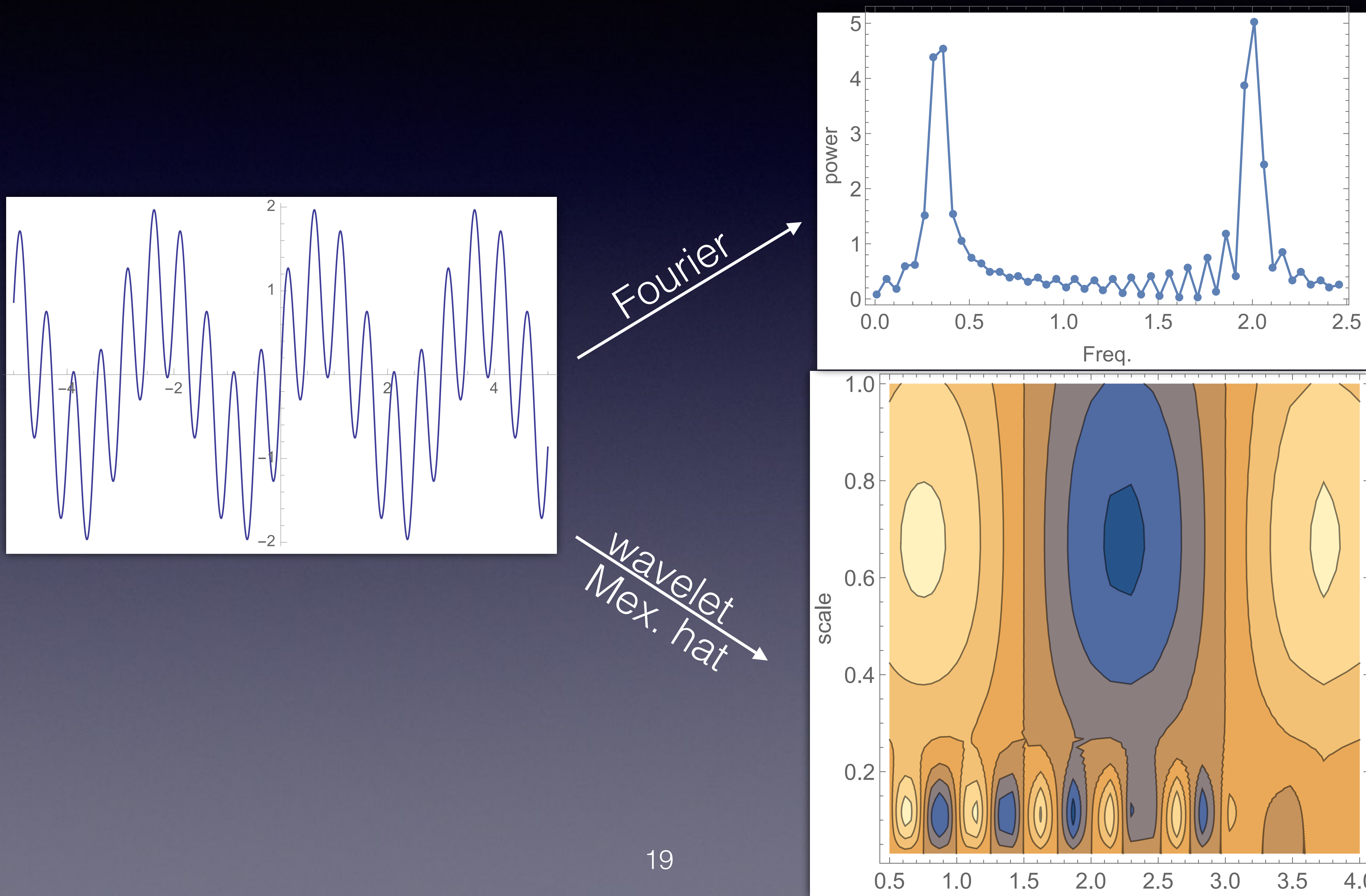
Fourier



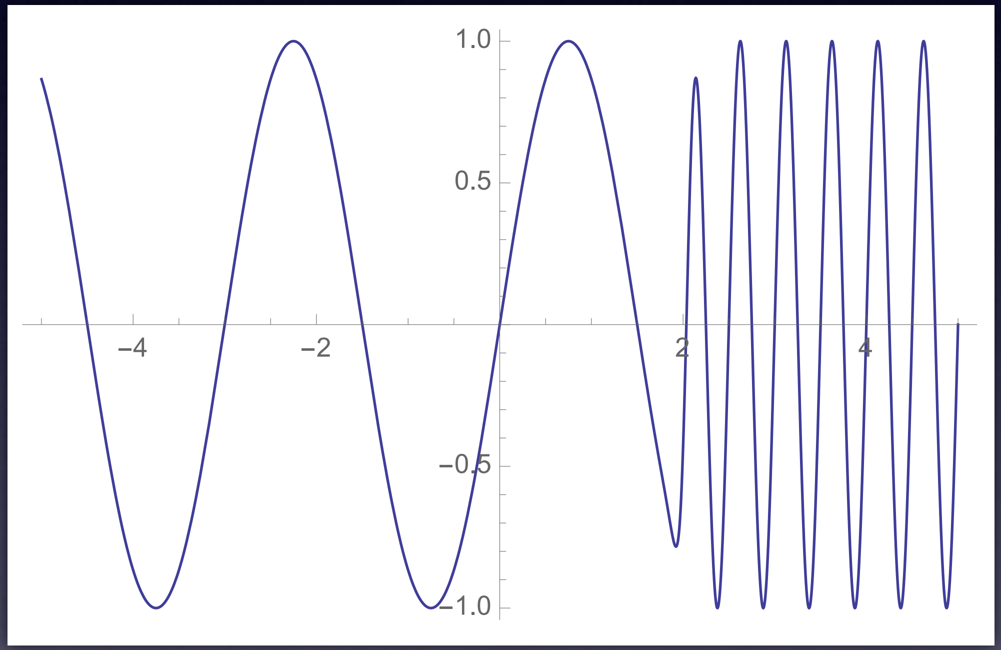
wavelet
Mex. hat

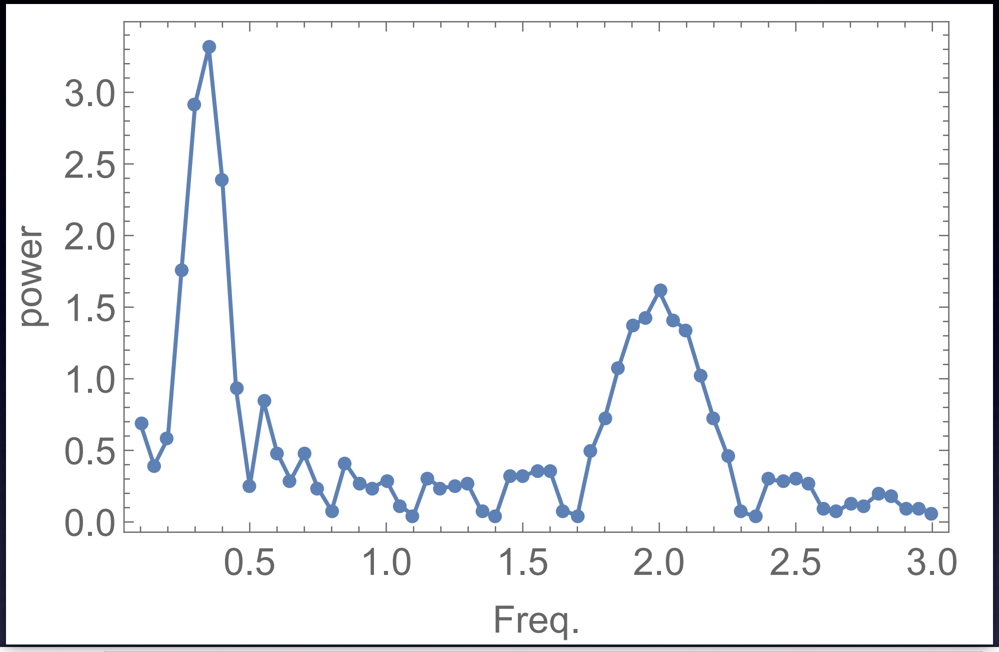


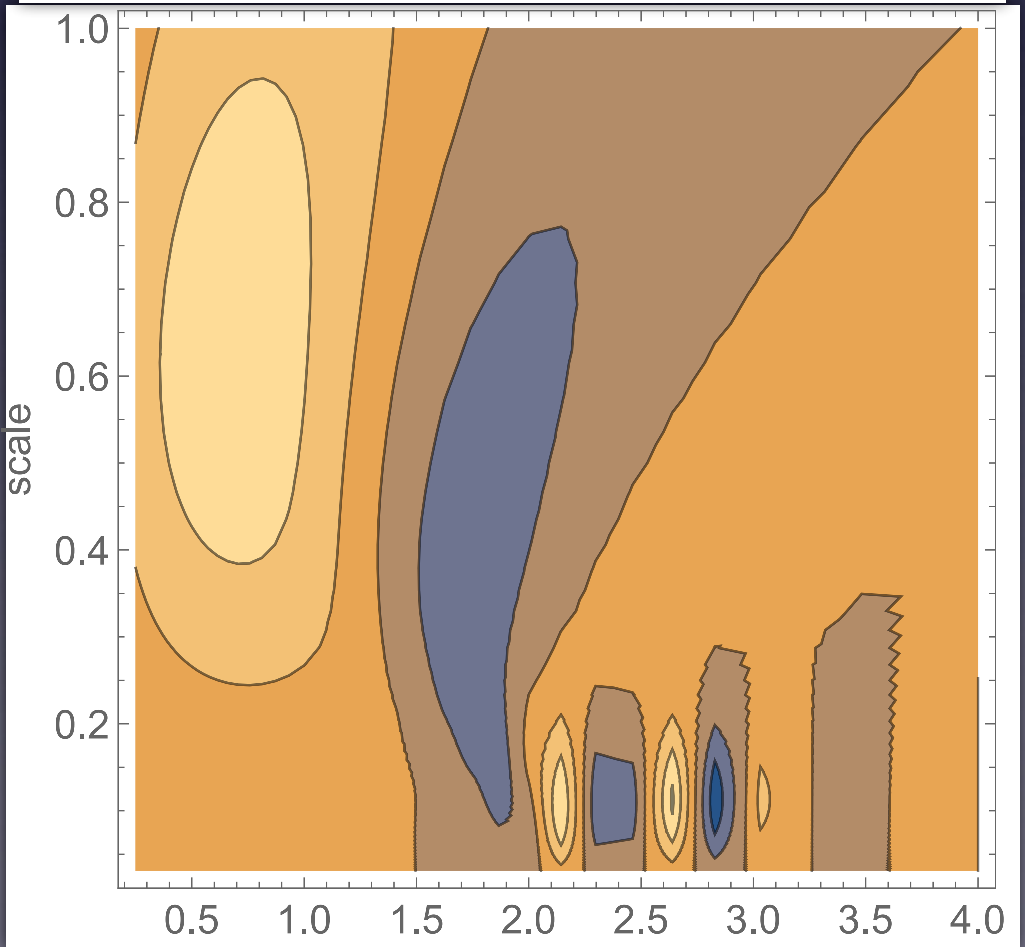
two sine waves



sine waves with transition







How might this approach improve upon templates?

GeV sky can be thought of as a high resolution picture; wavelets can find structures in it

Poisson noise and SM uncertainty dominate at scales that are small relative to bubbles or NFW, and the wavelets can identify those scales

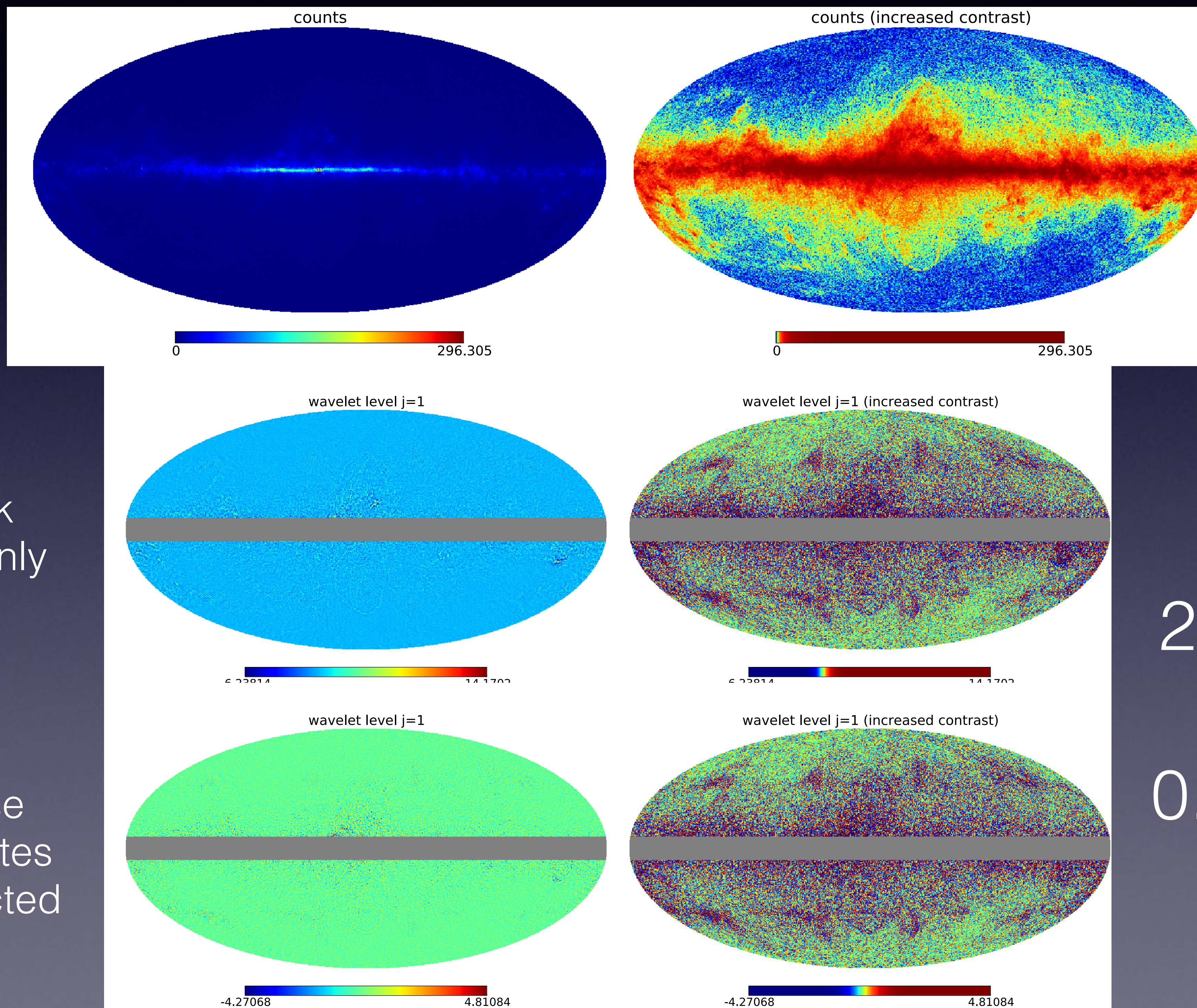
How might this approach improve upon templates?

GeV sky can be thought of as a high resolution picture; wavelets can find structures in it

Poisson noise and SM uncertainty dominate at scales that are small relative to bubbles or NFW, and the wavelets can identify those scales

by identifying and removing such structures, wavelets provide a background expectation that is (relatively) robust against systematic astrophysics uncertainties

Example (mock data)



ℓ_{max}=512

mock
data only

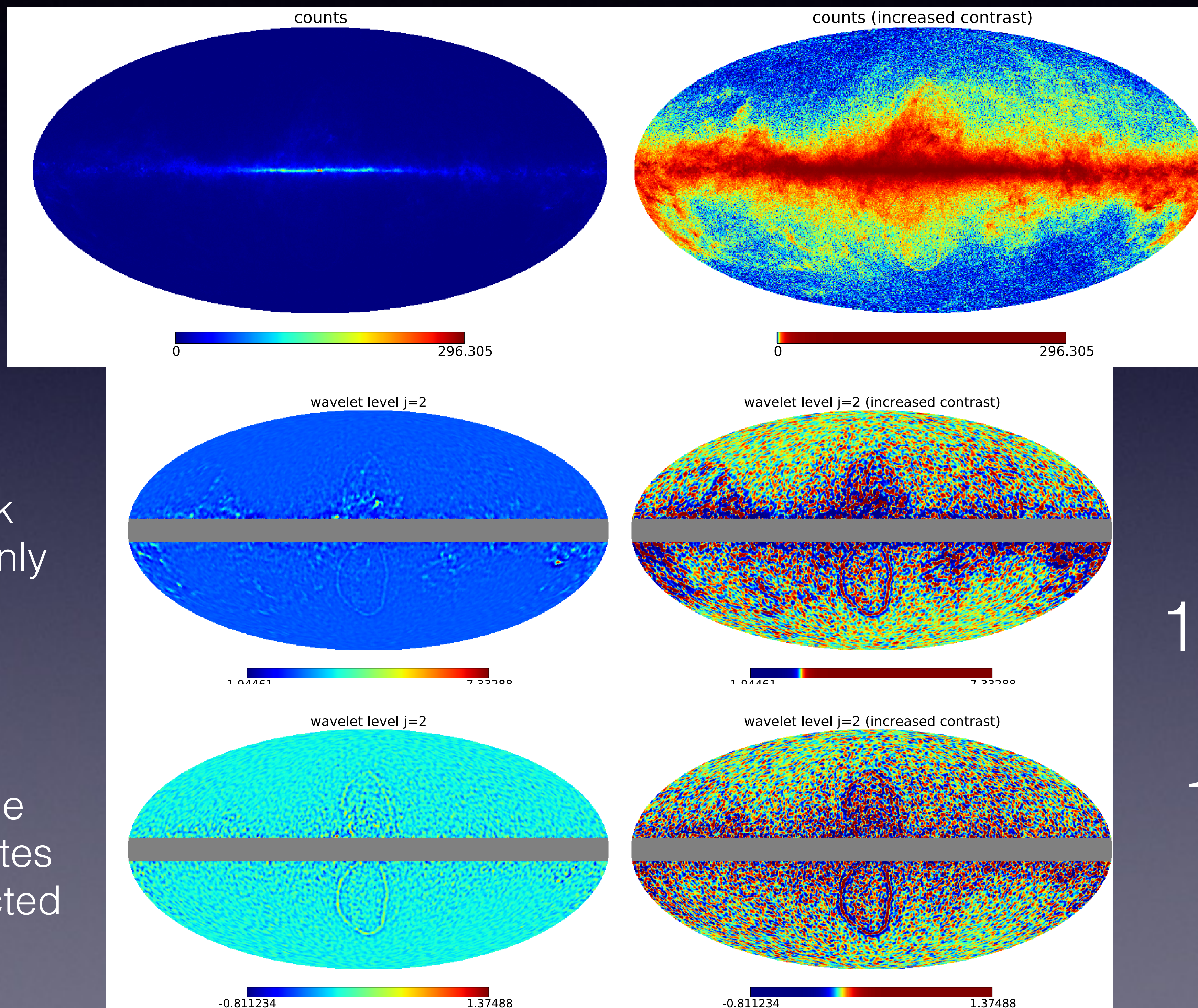
diffuse
templates
subtracted

$256<\ell<512$

$\Downarrow$

$0.7^\circ<\theta<1.4^\circ$

Example (mock data)



$\ell_{max}=512$

mock data only

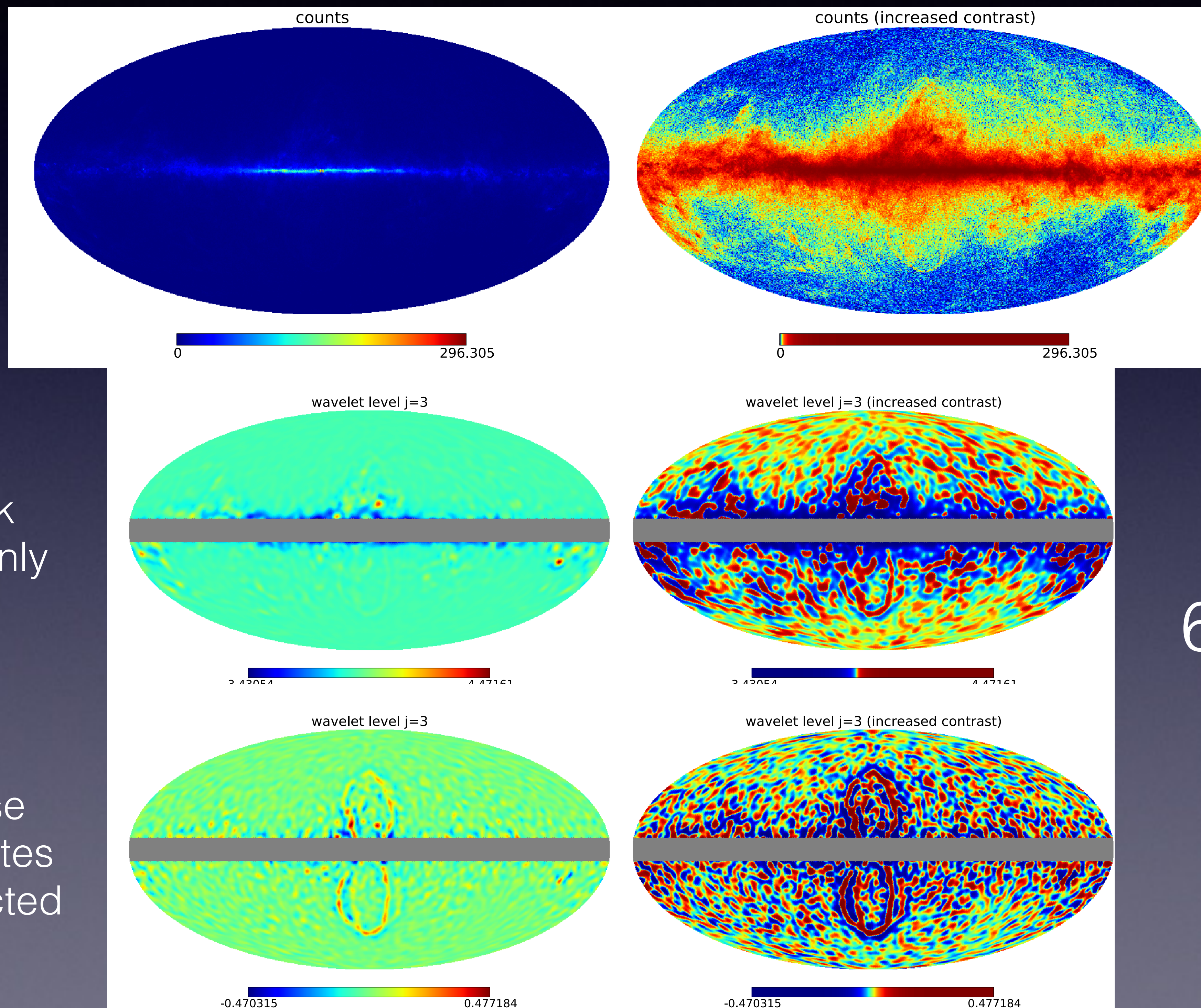
diffuse templates subtracted

$128<\ell<256$

$\Downarrow$

$1.4^{\circ}<\theta<3^{\circ}$

Example (mock data)



$\ell_{max}=512$

mock data only

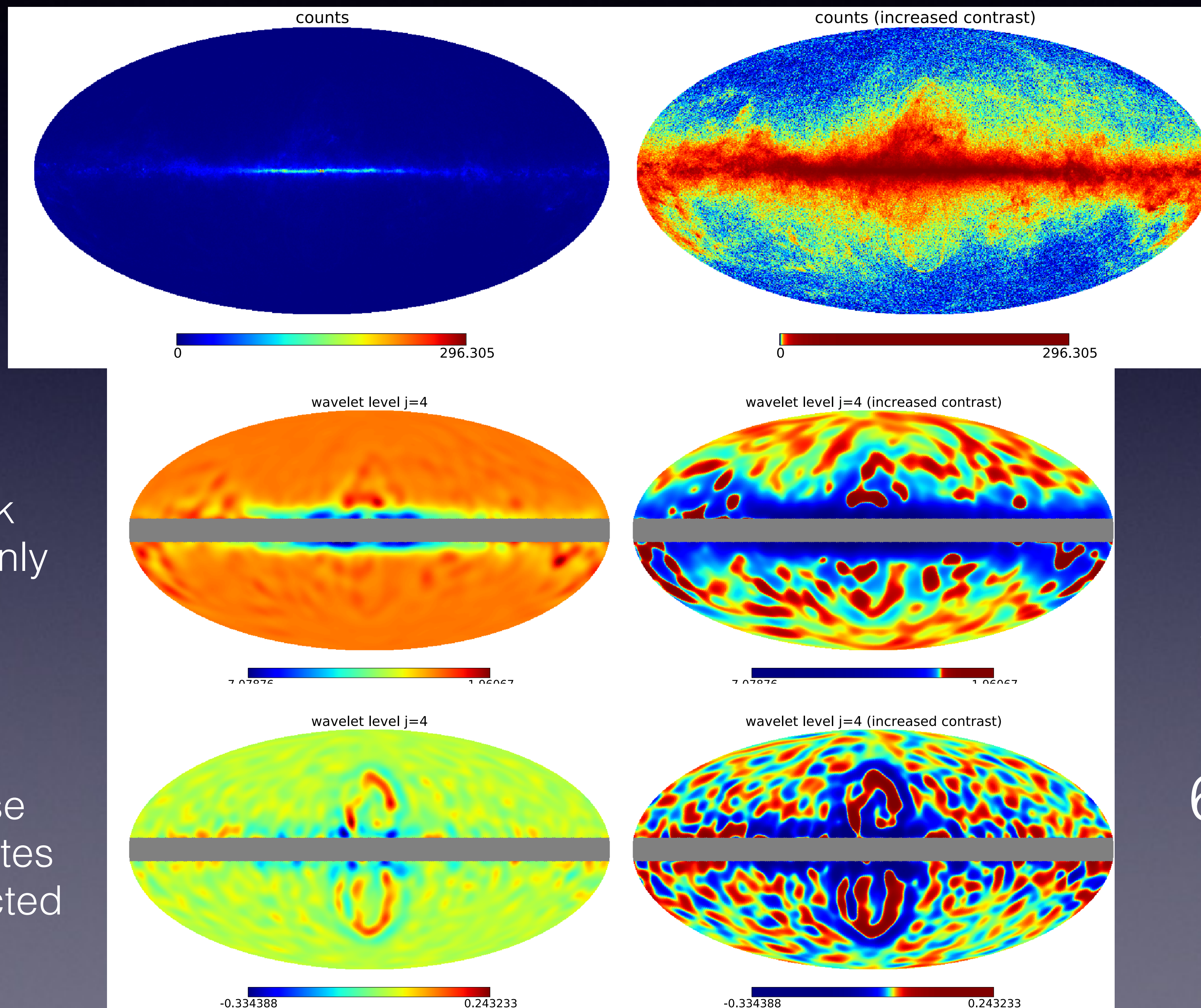
diffuse templates subtracted

$64<\ell<128$

$\Downarrow$

$3^{\circ}<\theta<6^{\circ}$

Example (mock data)



$\ell_{max}=512$

mock data only

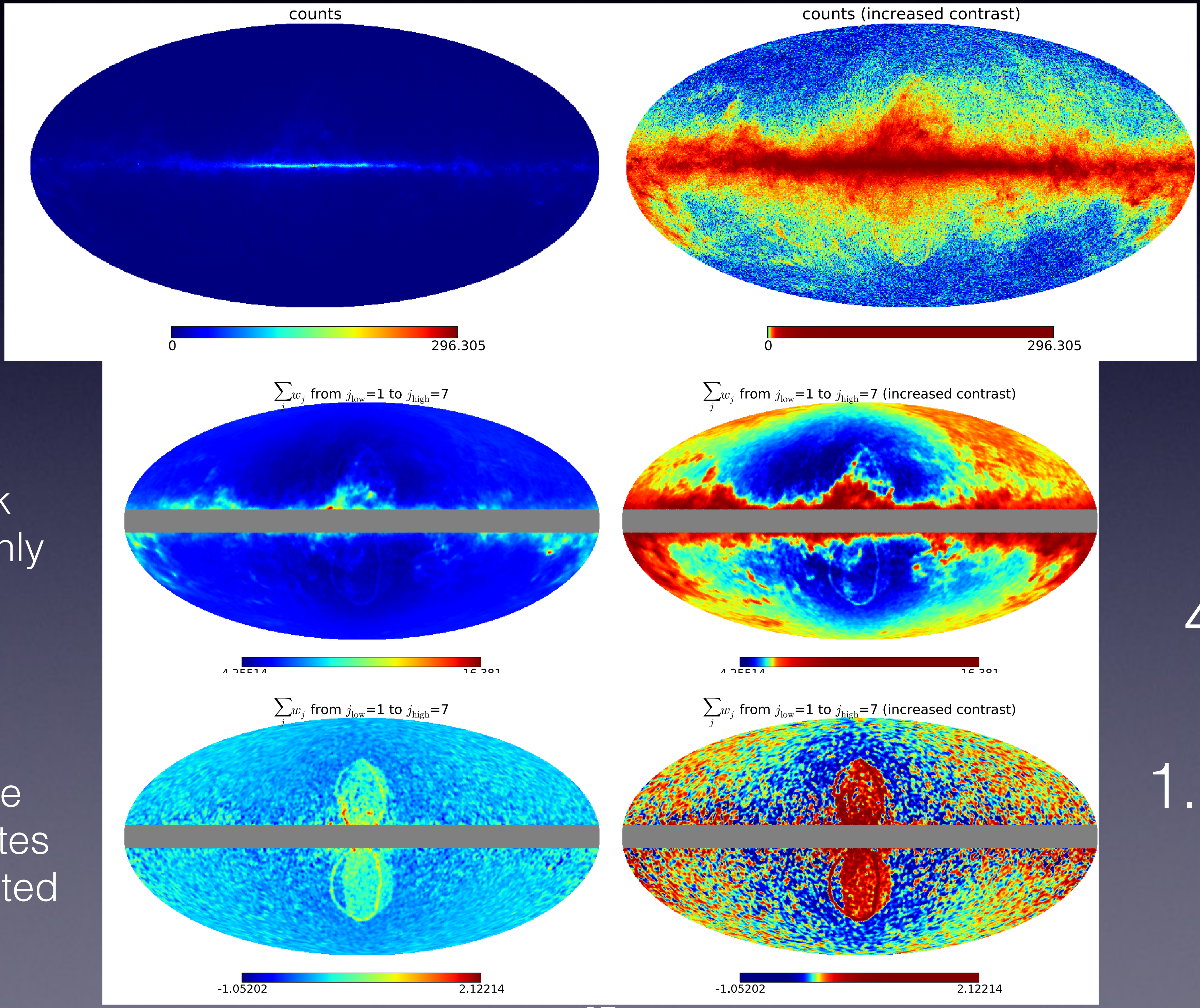
diffuse templates subtracted

$32<\ell<64$

$\Downarrow$

$6^\circ<\theta<10^\circ$

Example (mock data)



ℓ_{max}=512

mock
data only

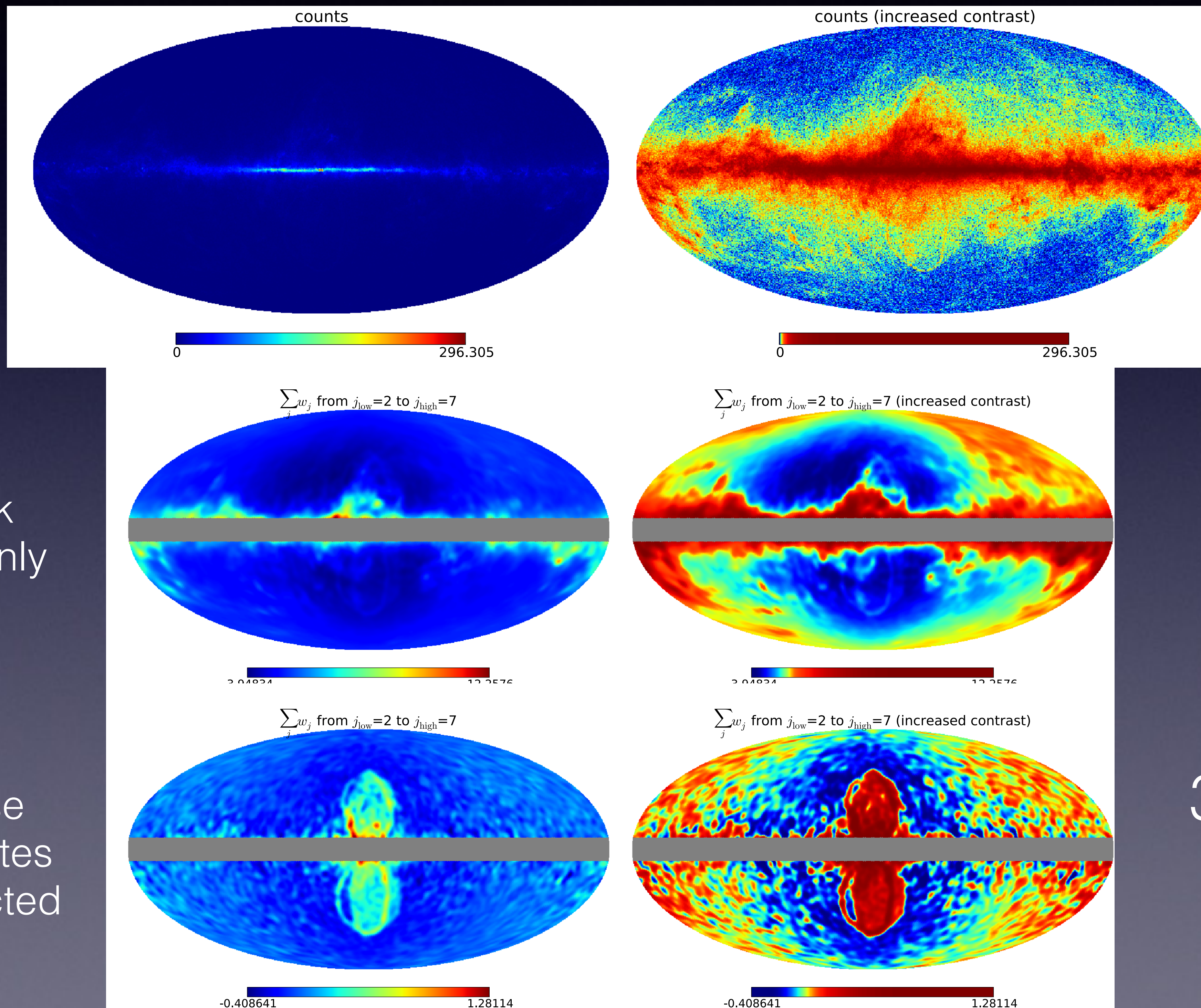
$4<\ell<256$

$\Downarrow$

$1.4^\circ<\theta<90^\circ$

diffuse
templates
subtracted

Example (mock data)



$\ell_{\rm max}$=512

mock data only

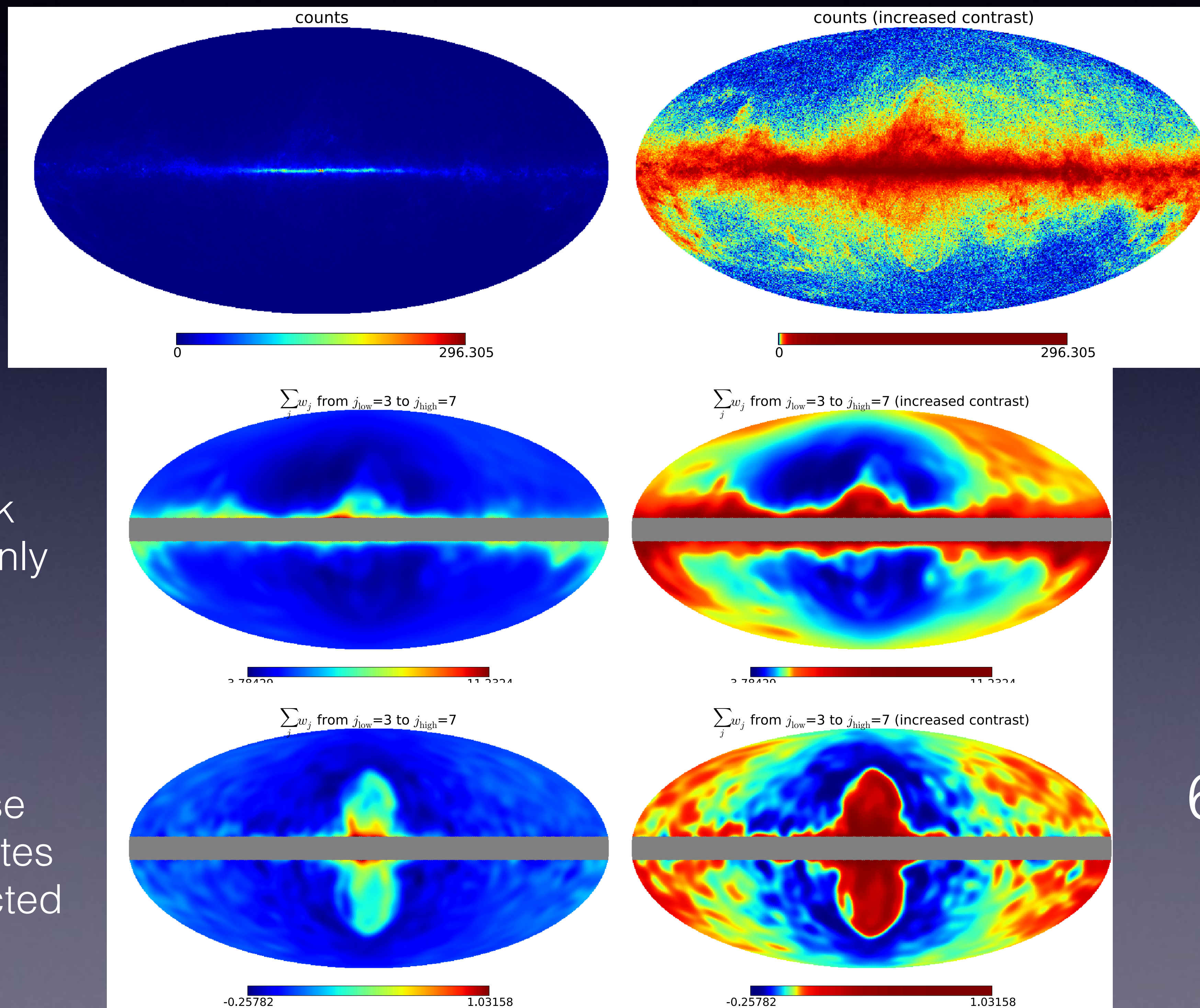
diffuse templates subtracted

$4<\ell<128$

$\Downarrow$

$3^\circ<\theta<90^\circ$

Example (mock data)



ℓ_{max}=512

mock
data only

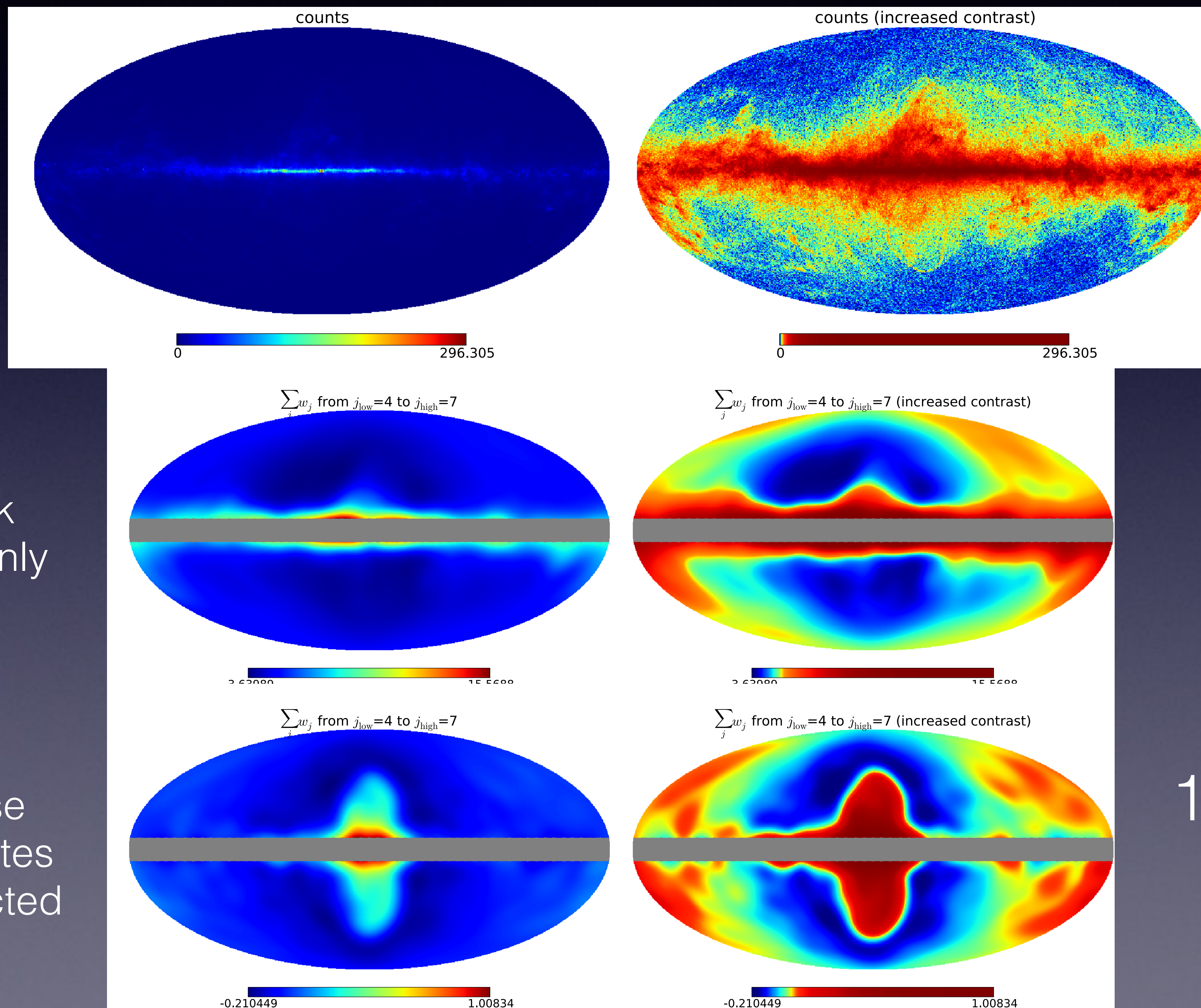
diffuse
templates
subtracted

$4<\ell<64$

$\Downarrow$

$6^\circ<\theta<90^\circ$

Example (mock data)



ℓ_{max}=512

mock
data only

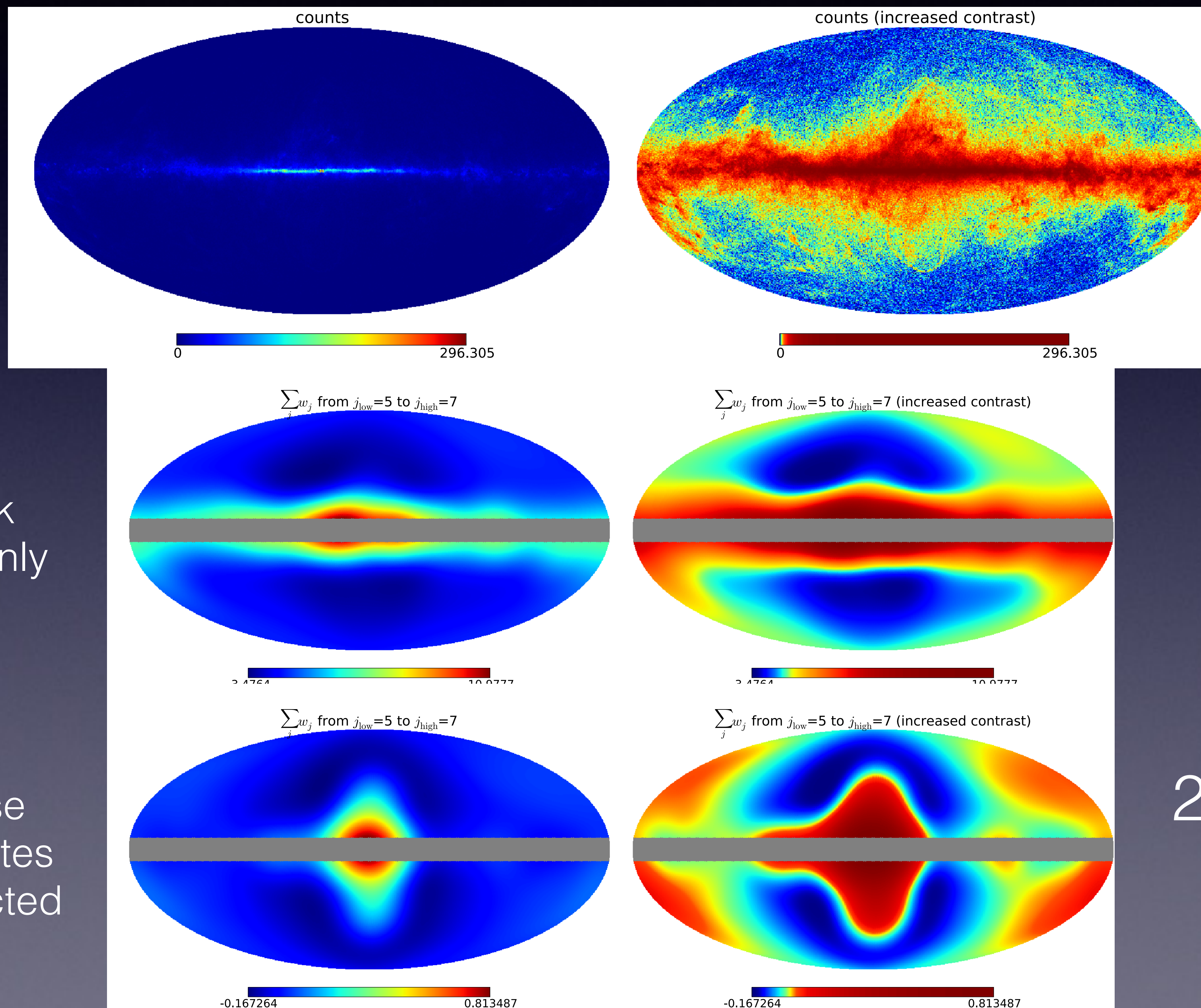
diffuse
templates
subtracted

$4<\ell<32$

$\Downarrow$

$10^\circ<\theta<90^\circ$

Example (mock data)



ℓ_{max}=512

mock data only

diffuse templates subtracted

$4<\ell<16$

$\Downarrow$

$22^\circ<\theta<90^\circ$

Lesson:

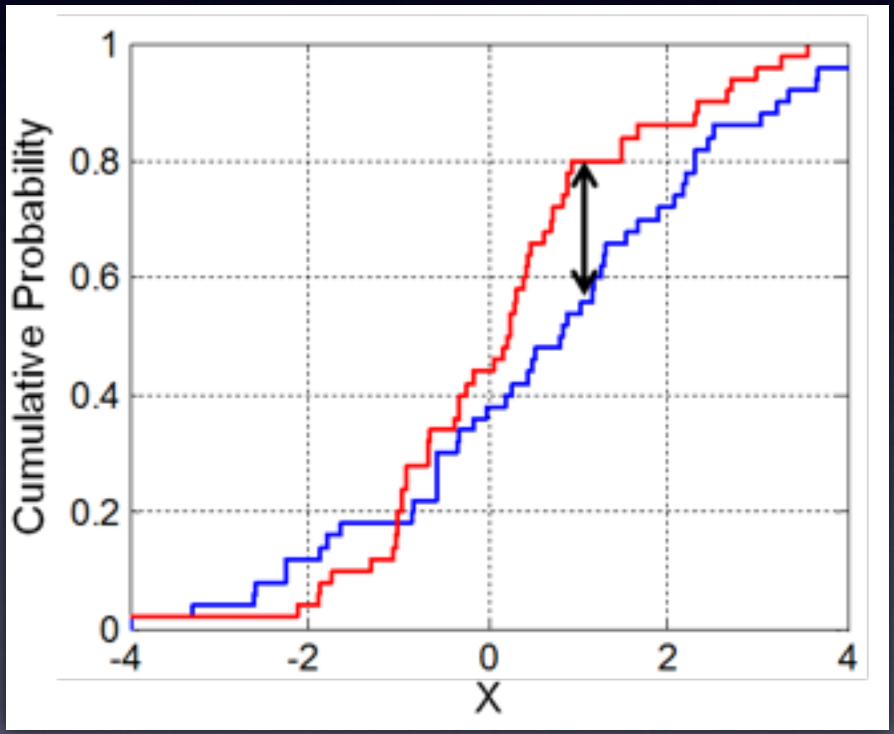
Getting rid of some wavelet levels can provide a much clearer picture of a signal

Question:

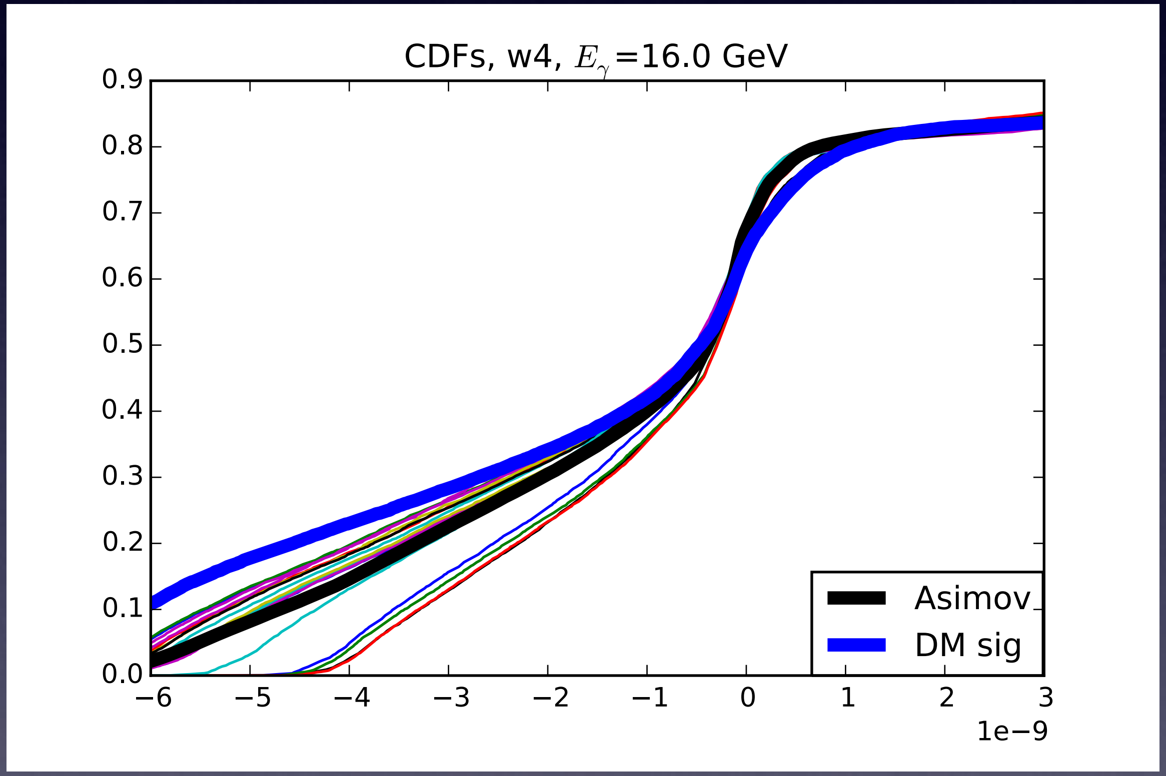
How can we do this in a data-driven (model-independent) (unbiased) (etc….) way?

Kolmogorov-Smirnov Test

maximum distance between two CDFs

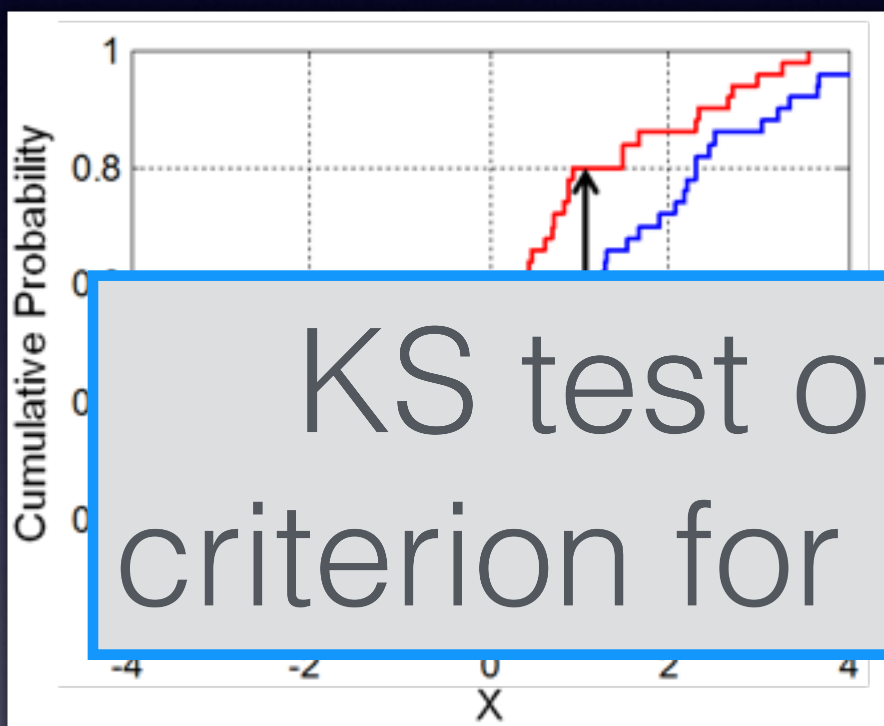


"KS2 Example" by Bscan - Own work. Licensed under CC0 via Commons - https://commons.wikimedia.org/wiki/File:KS2_Example.png#/media/File:KS2_Example.png

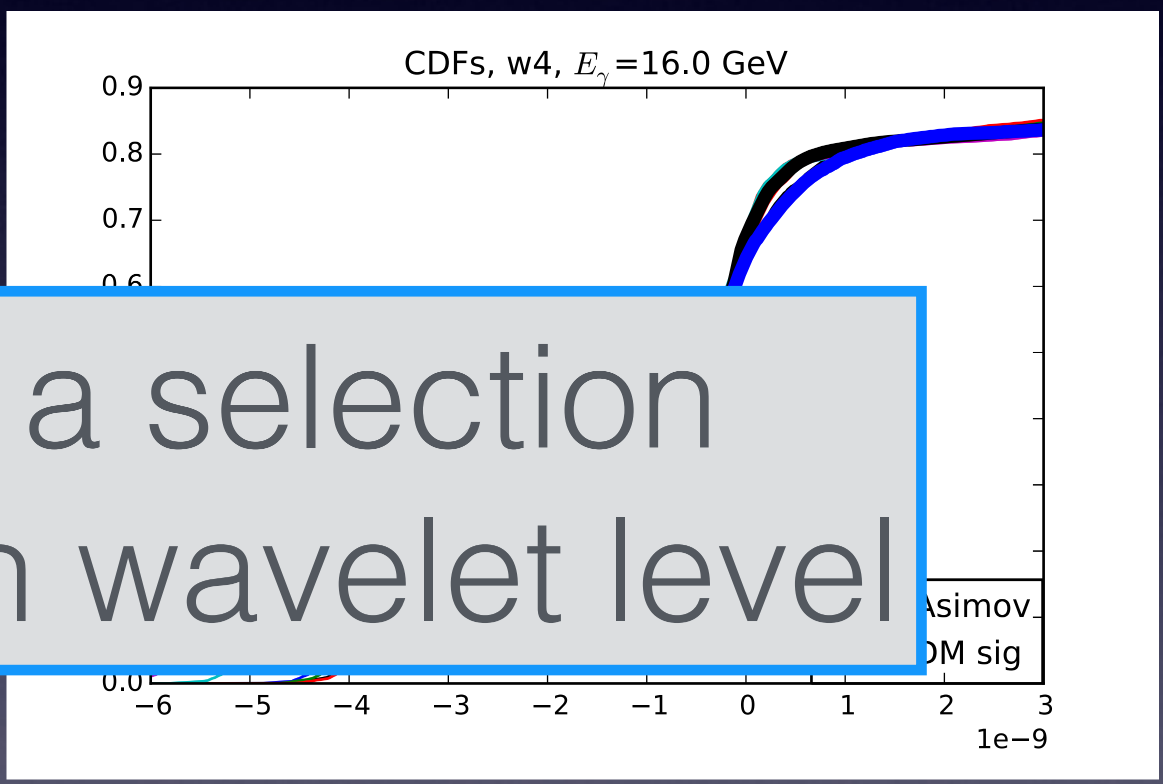


Kolmogorov-Smirnov Test

maximum distance between two CDFs



"KS2 Example" by Bscan - Own work. Licensed under CC0 via Commons - https://commons.wikimedia.org/wiki/File:KS2_Example.png#/media/File:KS2_Example.png



KS test offers a selection criterion for each wavelet level

“Thresholded” wavelets

signal = S

set of backgrounds = $\{B_i\}$

$$w_j^{>} = \begin{cases} w_j & \text{if KS}(S \mid \text{Asimov}) > 40\%\ \text{KS}(B_i \mid \text{Asimov}) \\ 0 & \text{otherwise} \end{cases}$$

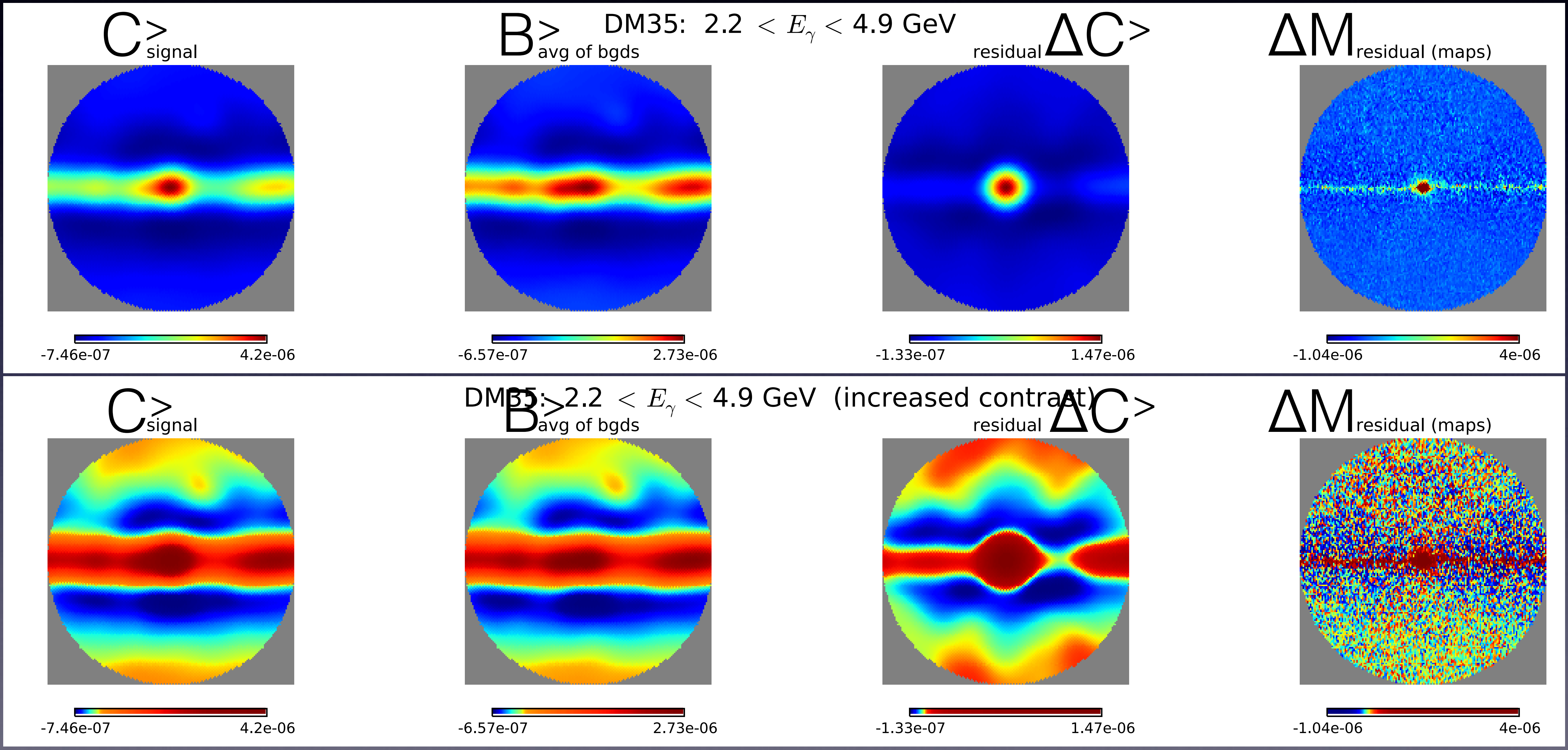
define “cleaned maps:” $C^{>} = \Sigma^{8}_{j=2}\, w_j^{>}(S)$

$$B_i^{>} = \Sigma^{8}_{j=2}\, w_j^{>}(B_i)\Theta[w_j^{>}(S)]$$

$$B^{>} = \text{avg}(\{B_i^{>}\})$$

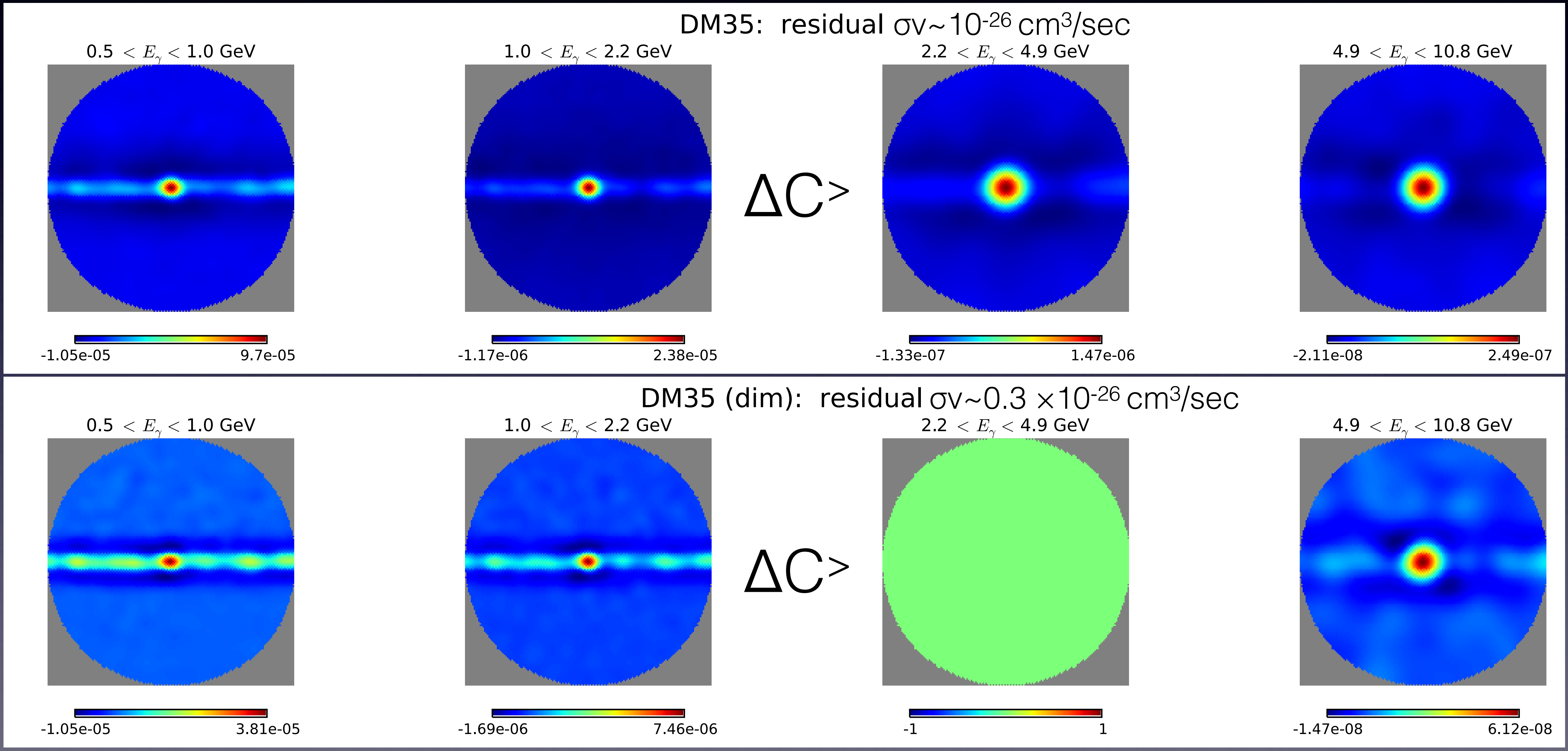
and “cleaned residual:” $\Delta C^{>} = C^{>} - B^{>}$

Cleaned Map Method



wavelets provide clearer residual than maps

Cleaned Map Threshold

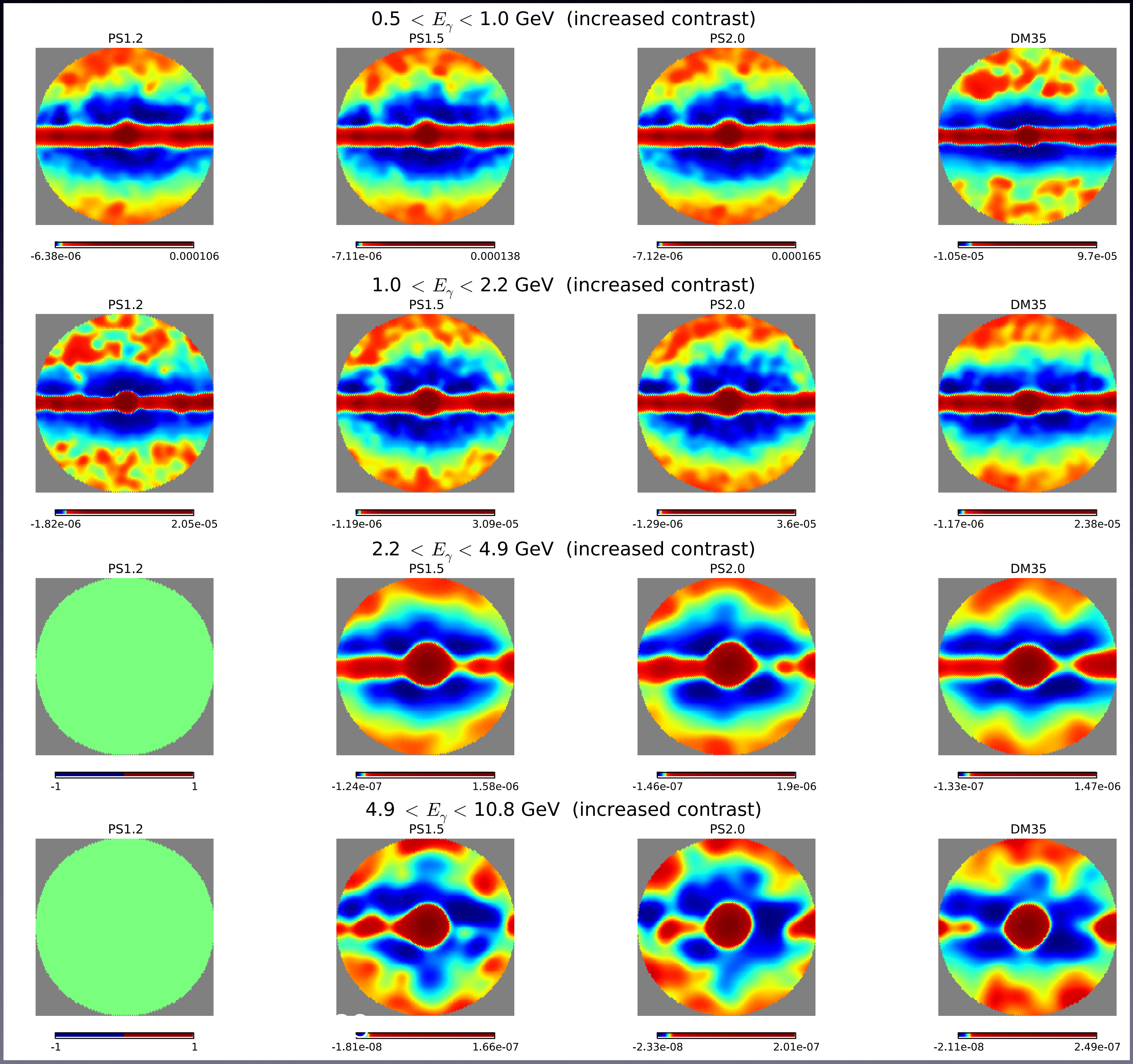


30% as bright is much harder to see

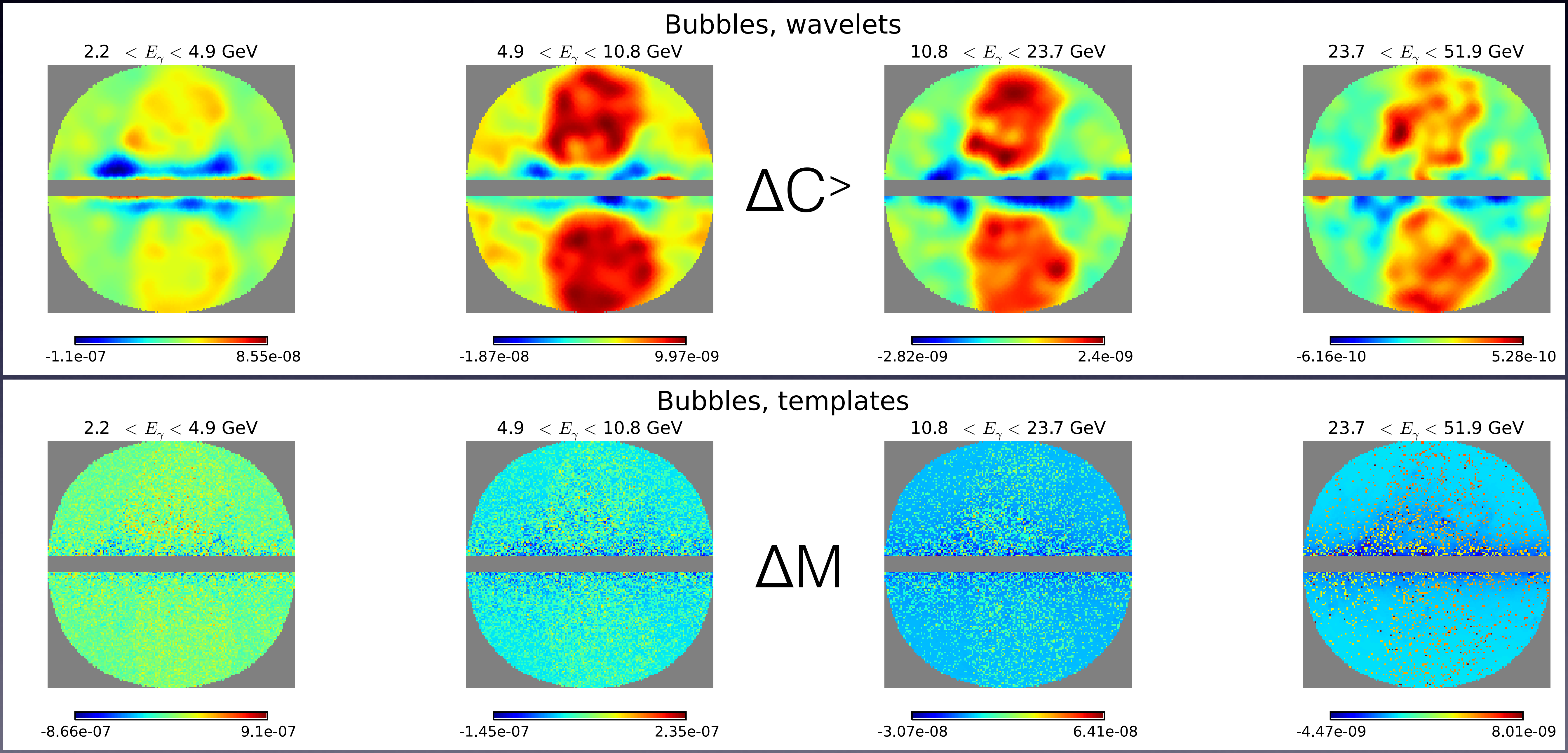
DM vs. Point Sources?

$L \sim L_0^{-\alpha} e^{-L/L_c}$

keep $\int L$ fixed



Cleaned Map, Bubbles



What are wavelets?

Allow analysis sensitive to both position and size

↓

different structures have “power” at different levels of the decomposition (edges = sharp variation, important first; larger scale objects = broader variation, important later)

↓

wavelets find structures, and the GCE is a qualitatively new structure that we ought to learn more about

Conclusions

Galactic center gamma ray excess is exciting to follow, but still so much more to learn about it

Need some less-model-dependent information

Wavelets are a promising tool for learning about this data

Conclusions

Galactic center gamma ray excess is exciting to follow, but still so much more to learn about it

Need some less-model-dependent information

Wavelets are a promising tool for learning about this data

$\boxed{\textbf{Much more to do!}}$

Thanks!